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Title: A Novel Approach to Gamma-Ray and Neutrino Astro-Particle Physics: The GRANDE Experiment

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A Novel Approach to Gamma-Ray and Neutrino Astro-Particle Physics: the GRANDE Experiment

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ABSTRACT

The GRANDE experiment is a unique "next-generation" detector capable of making significant contributions to the fields of ν and γ-ray astrophysics as well as performing important "conventional" high-energy physics investigations. The detector, which covers an area of 250 m x 250 m, is based on the well proven water Čerenkov technique. It will have excellent coverage for potential sources of ν emission in the southern hemisphere and of VHE and UHE sources in the northern hemisphere. For VHE and UHE showers, the low threshold ($\leq$10 TeV) and complete coverage for all three shower components (electromagnetic, muonic, and hadronic), are unique. Excellent angular resolution, $<1°$ for ν's and $<0.3°$ for γ-rays, large acceptance, good energy resolution, and wide energy sensitivity will permit detailed studies of the observed signals enabling a quantitative confrontation with theoretical predictions. The detector and some of its physics capabilities will be described.

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There has been great excitement recently in the field of high-energy astrophysics. At both VHE (100 GeV-10 TeV) and UHE (100 TeV-10 PeV) energies, γ-rays have been observed from several sources including Cygnus X-3 and, most recently, Hercules X-1.[1] In particular, the detection of Hercules X-1 provides the most compelling evidence to date for the existence of sources as well as of new particle physics at UHE energies; the source was detected independently by three groups and an anomalously large number of muons accompany the air showers detected from the source. It seems that x-ray binary sources provide a unique environment for the acceleration of particles to extremely high energies. Yet, there remains several unsolved questions about these sources, including γ-ray production at the source and its interaction in the atmosphere. The acceleration mechanism at the source is unknown, although it is speculated that the x-ray binary accelerates hadrons which interact with a "beam-dump" to produce neutral pions which then decay into photons. Perhaps the only truly convincing evidence of this process would be the detection of the high energy ν's which must accompany the photons if they are produced in this way. Correlated observations of both ν's and γ-rays from the same or similar sources would also aid in understanding the acceleration mechanism. The number of muons in the air-showers from these sources, expected to be more than an order of magnitude less than in hadronic air-showers, seems to be comparable to that in hadronic air-showers. This implies the presence of new physics beyond the standard model of particle physics. Crudely speaking, the anomalous number of muons could be due to either a new interaction of a known particle or an as-yet-undetected new particle. If it is a new interaction of a known particle, then, below some threshold energy, that interaction must "turn-off" and the particle must interact normally; therefore, below the threshold energy the muon content of the air-showers should appear normal. Conversely, if it is a new particle, the muon content should remain abnormal at low energies. Further, the presence or absence of a hadronic core in the shower will lend an important clue about the particle physics responsible for the anomalous muons. Future solutions to these puzzles will require detectors with new and unique capabilities.

The GRANDE (Gamma Ray And Neutrino DEtector) facility is a dual purpose experiment designed to help solve some of these puzzles. It will search for both VHE-UHE γ-ray and high-energy ν sources and is based on the well developed water Čerenkov technique. The conceptual design of the detector is shown in Figure 1. It covers an area of 250 m x 250 m and consists of two semi-independent detectors: the γ-ray telescope and the ν telescope. The Air Shower Array (ASA) part of the detector consists of two optically isolated planes of upward facing photomultiplier tubes (PMTs) spaced on a 6 m lattice, the top plane to detect the electromagnetic and hadronic components of the air shower and the lower plane to detect the muonic component. The Neutrino Telescope (TNT) part of the facility consists of three downward-facing optically isolated planes of PMTs, with the same lattice spacing, used to reconstruct the direction and energy of upward-going muons induced by ν's below the detector. A brief description of the function and performance of each detector follows; more details can be found in [2].

As mentioned, the ASA is composed of two layers of PMTs, their function shown schematically in Figure 2. The top layer of PMTs, located 10 m below the surface of the water, also known as the "shower calorimeter" layer, serves two purposes; it permits the determination of the direction and energy of the shower, and the identification of hadrons in the shower. Each particle in the shower that strikes the water produces Čerenkov light which is detected by the PMTs; the amount of Čerenkov light produced depends on the particle's energy, mass, and on the Čerenkov threshold. The Čerenkov equivalent energy,

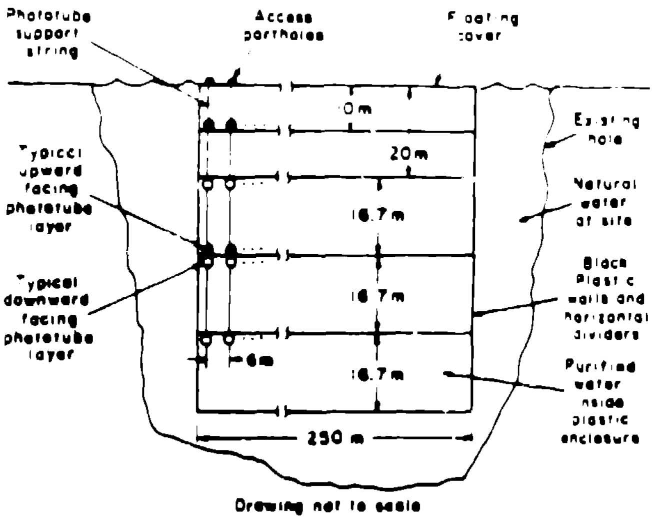

Figure 1: Schematic of GRANDE showing dimensions of the detector. The circles represent the locations of PMTs.

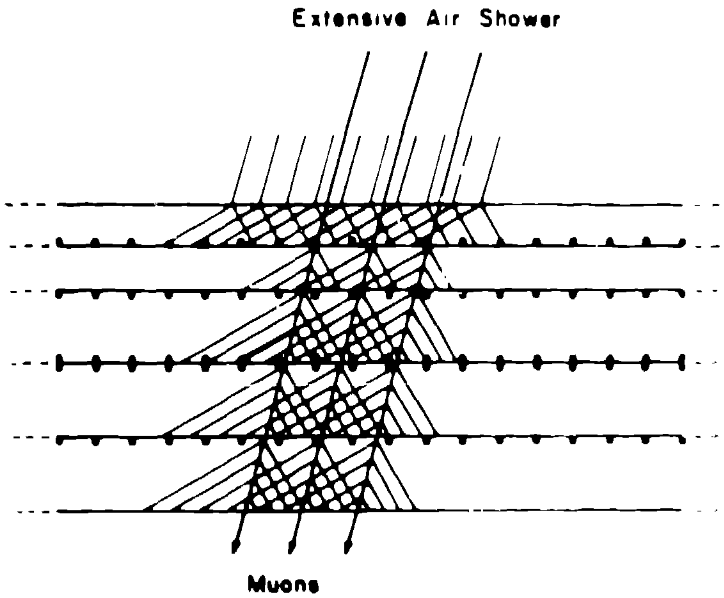

Figure 2: Schematic of EAS in GRANDE showing the function of the shower and muon layers (dark circles). The lines radiating from the shower particles represent the Čerenkov light produced in the water.

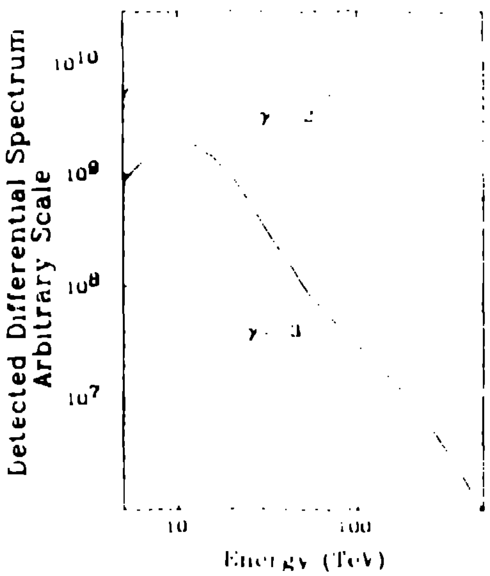

Figure 3: Differential spectrum of detected events assuming two hypothetical differential source spectral indices.

or "visible energy," E_c, of a particle is defined as the energy an electron would need in order to produce the same amount of light. With this definition, the following relations hold:

E_c	$=$	E	for electrons (by definition)
E_c	$=$	E	for gammas
E_c	$\simeq$	E - 200 MeV	for muons
E_c	$\simeq$	E/2	for high-energy hadrons ($\geq$ 10 GeV)

In the GRANDE configuration, about 1 photoelectron is produced for every 120 MeV of visible energy. In this way, the energy deposited in the shower calorimeter layer can be determined.

Since GRANDE measures the total energy content of the shower, and not just a small fraction of the number of charged particles, it is able to operate at a much lower threshold (about 10 TeV) than can conventional air shower experiments. Figure 3 shows the differential number of events detected by GRANDE for two hypothetical source spectra. Clearly, GRANDE will be quite sensitive to showers extending to primary energies as low as 5 TeV.

The direction of the shower is determined from the timing pattern of the detected Čerenkov light. For example, the resolution, defined as the mean of the angular difference distribution, is found to be about 0.3° for low energy (~10 TeV) γ-ray primaries observed at sea level. For sources of showers which contain an anomalous number of muons, the PMT hits in the muon layer can also be used to make an independent determination of the air shower direction, thus improving the angular resolution.

This brings up an interesting possibility for examining such sources which has yet to be studied in detail. When a source which produces these showers is low on the horizon, the low energy air showers will not penetrate the atmosphere to reach the detector. Nevertheless, the muons produced in the air shower will reach the detector and can trigger

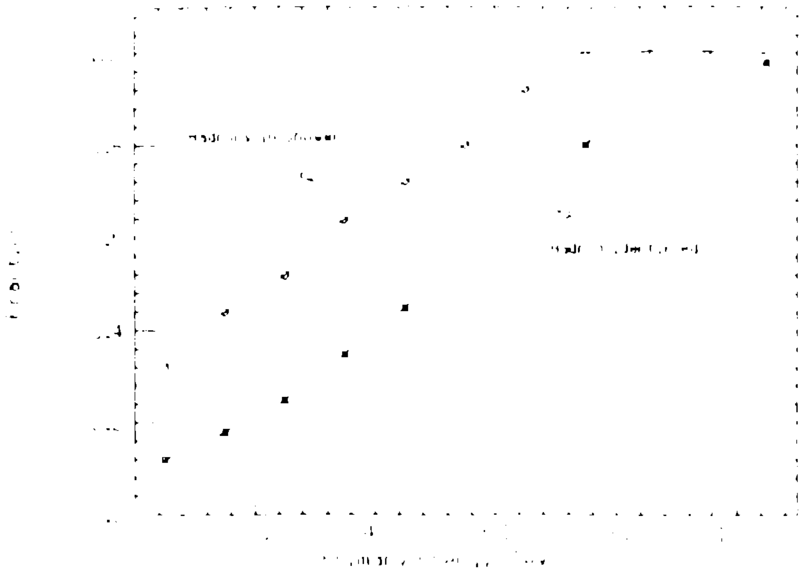

Figure 4: The fraction of events with a hadron remaining in the shower as a function of proton primary energy. Also shown is the identification probability for those hadrons using the simp scheme described in the text.

it. This technique should allow more detector exposure to such low-energy showers and thereby increase the chance of detecting sources, especially those that burst or never pass near zenith.

The mechanism of the anomalous muon production in air-showers is completely unknown. An important clue to this mechanism would be the existence or absence of associated hadrons. For example, if the muon production is due to a primary which interacts strongly, then the leading hadronic secondary should reach the ground. To study this possibility and the detectability of hadrons in the presence of an air-shower, it is assumed that the primary interacts exactly like a proton. Figure 4 shows the fraction of showers which still contain a hadron as a function of primary energy. A simple technique has been developed which is based on the expectation that a high-energy hadron remaining in the air-shower as it strikes the ground will cause a shower in the water; the hadron will deposit more energy than normally expected and can then be detected as a local "hot spot" at the shower core. For showers landing on GRANDE, the probability of identifying the hadron in the shower is also shown in the figure. Thus, as expected, GRANDE will act as a simple hadronic calorimeter and will be able to search for hadrons accompanying the muons in air-showers providing an important clue as to the nature of the primary particle.

The second layer which composes the ASA portion of GRANDE lies 20 m below the surface of the water and is used to detect muons. It has been traditionally thought that muons would provide a discrimination factor between air-showers induced by γ ray primaries and hadronic primaries. If this is the case, then the capabilities of GRANDE for rejecting hadronic background is unprecedented. For example, for primary energies > 100 TeV, the rejection factor for hadronic primaries is at least 10,000 with no loss of γ-ray events. Instead, if a source such as Hercules X-1 is known to have events with anomalous muon content, those muons can be studied in great detail; their number distribution can

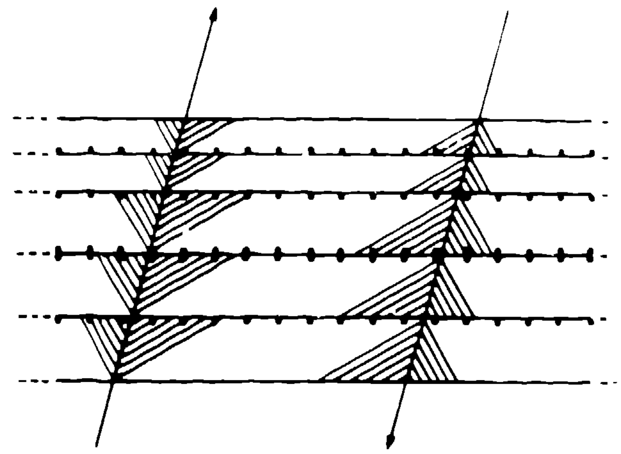

Figure 5: Schematic of downward- (cosmic ray) and upward-going (neutrino induced) muons passing through the neutrino portion of GRANDE. As shown, the downward-going muon illuminates very few PMTs while the upward-going one illuminates many; the difference in timing pattern between the two is also useful in determining up from down.

be accurately determined and their lateral distribution can be studied.

From this it can be concluded that the capabilities of the water-Čerenkov technique applied as an air-shower array yields superior performance over traditional scintillator based arrays. The design of GRANDE gives an angular resolution for a variety of event types of $\simeq 0.3°$. The capability of GRANDE for reconstructing air shower directions is about a factor of 3 better than any existing array (giving nearly 10 times better signal to noise) and about a factor of 2 better than any other planned array. In addition, the capabilities of GRANDE for detecting and studying the hadronic and muonic components of air-showers from VHE-UHE sources are unmatched in any other detector, either planned or proposed.

The neutrino portion of GRANDE is composed of three layers of downward facing PMTs. Figure 5 illustrates the principle allowing operation of TNT at the earths surface. A muon resulting from a neutrino interaction in the rock below the detector penetrates the bottom layer, producing a multi-tube coincidence. The muon continues through the second and third layers at later times. A neutrino event is signaled by observing the coincident sequence of three plane triggers. A variety of processes (for example, light scattering) allow a downward-going muon to occasionally produce PMT hits on the TNT portion of GRANDE. Detailed simulations of the downward going muon flux, including correlated muons in large showers, resulted in a trigger rate using this simple scheme of about 60 sec^{-1}. If we require the individual PMTs to have more than a few photoelectrons, we substantially reduce this rate since a downward muon usually produces only about 1 photoelectron in each PMT while an upward one produces several. Since most of the background events that trigger TNT are due to large showers of muons caused by VHE cosmic rays, these events will additionally have triggered and been recorded by the ASA. In this way, the ASA functions as an active veto for the TNT portion of GRANDE and most of the events that trigger the TNT are of interest to the ASA.

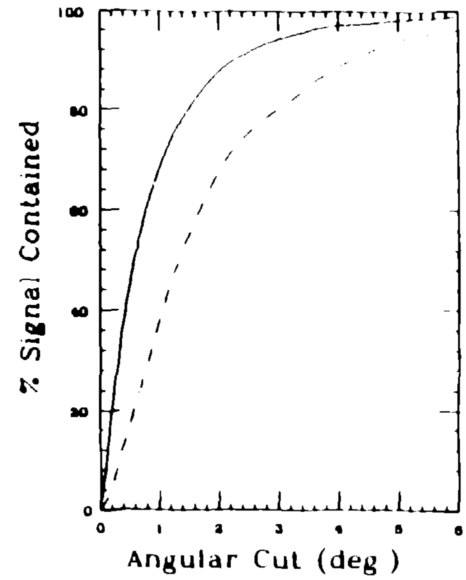

Figure 6: Integral fraction of muons within an angle θ of the initial neutrino direction for two hypothetical differential power law source spectral indices; $\gamma = 2.3$ (solid line) and $\gamma = 3.0$ (dashed line).

Of course, there is an unreducible background to astrophysical neutrino sources due to neutrinos produced in the atmosphere caused by the decay of secondaries in cosmic ray showers. This background is essentially isotropic with respect to any source and therefore is discriminated against by having good angular resolution. There is, however, an inherent minimum resolution caused by both the angular deviation in the neutrino interaction and the muon scattering in the rock on the way to the detector. Figure 6 shows the distribution of the angle between the original neutrino direction and the muon ν's direction when the muon strikes the detector; the integral distribution is shown for two hypothetical differential power law source spectra with spectral index 2.3 and 3.0. From this figure, it can be concluded that a determination of the muon direction with a precision much better than 1° is unnecessary.

The design of the TNT portion of GRANDE was made with this in mind; the goal was a design that would give a muon angular resolution of better than 1° . The final result is an average resolution of 0.8° . This resolution is nearly independent of the zenith angle and the entry point on the bottom plane of the detector.

The irreducible atmospheric neutrino background in GRANDE is calculated assuming an initial muon neutrino and antineutrino spectrum and the standard parton model of neutrino scattering. The resultant muons are propagated through the rock surrounding the detector including all of the relevant energy loss mechanisms and multiple Coulomb scattering. A total of one year of live time was simulated yielding 4750 events (13 per day) from atmospheric neutrinos. As an example, a 3° cut around the direction of Vela X-1 would yield a background rate of 5.6 events per year.

In fact, given the right circumstances, the "irreducible" atmospheric neutrino background is not really irreducible. It has been clear for a long time that, since the atmospheric neutrino background tends to have a much softer spectrum than that expected from a neutrino source, the signal-to-noise ratio increases with increasing neutrino energy. Thus, it would be beneficial to be able to identify relatively high-energy neutrino interactions. Further, isolation of a subset of the total atmospheric neutrino flux due to very high energy neutrinos would allow study of the weak interaction at high energies.

GRANDE will be able to isolate high-energy muons using the increase in Čerenkov light output because of the rapid rise in muon energy loss due to bremsstrahlung and pair production at E $\sim$ 1 TeV. To examine the energy discrimination of the detector, muons of varying energies (100 GeV - 10 TeV) entering GRANDE were simulated. A simple cut on the observed number of photoelectrons in a neutrino event will allow separation of those due to VHE ν interactions. For example, a cut requiring Npe > 200 removes about 97% of the atmospheric background while leaving about 50% of the signal. From this it can be seen that GRANDE is capable of achieving a high "threshold," long claimed to be a necessity in searching for astrophysical neutrinos, without sacrificing lower energy neutrino events.

Another intreaguing possible source of high-energy neutrinos is the sun. The existence of a particle known as a WIMP (Weakly Interacting Massive Particle) was postulated to help explain the "missing matter" or "dark matter" that must exist in our galaxy. This particle is thought to be one of a variety of new particles speculated to exist but not yet observed. Given the right elastic scattering cross section, they may interact with the sun, become gravitationally bound, and accumulate near the solar core. If these WIMPs are elementary, they must have been produced in the early universe in equal abundances of particle and antiparticle; particle-antiparticle annihilations in the sun would produce lepton pairs which then could produce neutrinos. The sensitivity of GRANDE to this process has been calculated in detail, including fragmentation effects and effects of the solar interior.[3] Since the branching ratio of WIMP annihilation is model dependent, the sensitivity is taken to be the annihilation rate divided by the final state branching ratio assuming each final state is responsible for 10 events per year in GRANDE; the results are shown in Figure 7. The atmospheric background is expected to be about 4 events per year. A simple model[4] which assumes the WIMP to be a supersymmetric photino yields an annihilation rate of $5\times10^{26}\Omega\sigma_{36}/M$ where Ω is the relic WIMP density relative to closure density and σ_{36} is the WIMP-nucleon elastic scattering cross section in units of 10^{-36}cm^2 and M is the WIMP mass in units of 100 GeV. Clearly, GRANDE will provide excellent sensitivity for such processes in the sun.

In conclusion, in evaluating the capabilities of a water Čerenkov detector such as GRANDE, we have demonstrated several important points:

1. Neutrino astronomy is feasible at the earth's surface-it is unnecessary to go underground or underwater.

2. The water Čerenkov technique has excellent prospects and is perhaps the first new technique for gamma-ray astronomy in decades.

3. GRANDE can be built in just a few years-there are no new techniques or technologies required.

The size of GRANDE is the next reasonable step up for neutrino detection from current underground detectors and is large enough to be very sensitive for gamma-ray studies. Conversely, because of the low fluxes expected from these sources, neutrino astronomy, as well as gamma-ray astronomy, requires such a large size detector. Detection of astrophysical sources of gamma-rays and neutrinos will provide unique information potentially

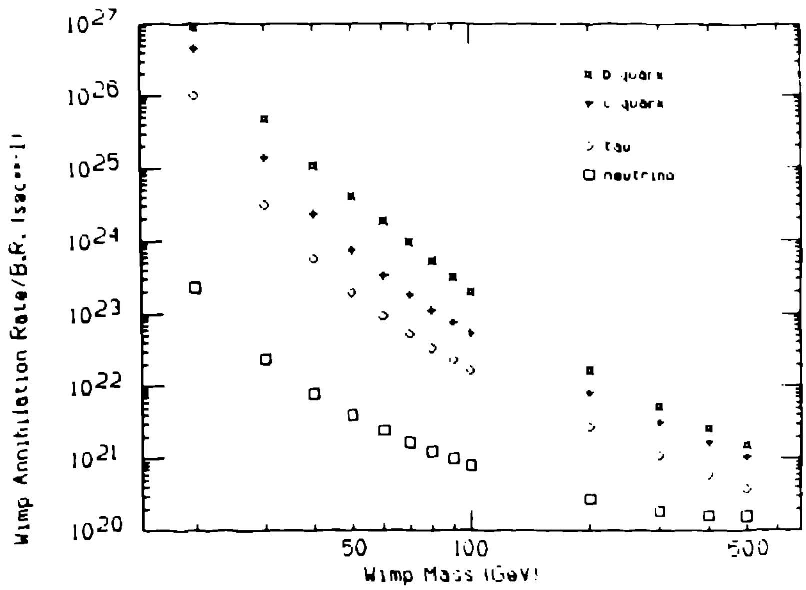

Figure 7: Sensitivity of GRANDE to WIMP annihilation in the sun as a function of the WIMP mass.

allowing us to understand the nature of the sources as well as the nature of gamma-rays and neutrinos themselves.

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